Department of Electrical, Computer, and Energy Engineering
University of Colorado, Boulder

A Disruptive Approach to Electric Vehicle Power Electronics

R. Erickson (PI), D. Maksimovic, K. Afridi

Annual Merit Review

June 2017

DOE Vehicle Technologies Program

FOA: Vehicle Technologies Incubator
Area: Power Electronics—Topologies
Project ID: EDT072

Overview

Timeline

Start date: January 1, 2015

End date: December 31, 2016
(no cost extension to 6/30/17)

Percent complete: 100%

Budget

Total project funding: $2,501,093

DOE share: $1,998,658

Cost share: $502,435

Barriers / Project Goals

- Traction drive system efficiency > 94%
- Power electronics system density > 13.4 kW/L
- Power electronics specific weight > 14.1 kW/kg
- Power electronics cost < $3.3/kW
- Exceed on-board charger target of 3.3 kW, < 3.5 kg added weight

Power electronics: innovative topologies

Subcontractor

Wolfspeed/Cree

900 V and 1200 V SiC MOSFET devices

Packaging of SiC semiconductor modules

High density system packaging

Relevance

Project addresses APEEM R&D goals: Innovative power electronics topologies that improve traction drive system size, cost, weight, and efficiency

APEEM 2020 Goal	Goals of this Project
Traction drive system (power electronics plus motors): Efficiency > 94%	• Power electronics US06 average efficiency improved from 92.5% to 97.5%: 30 kW drivetrain architecture demonstration
Power electronics density > 13.4 kW/L	• WBG high density demonstration: > 13.4 kW/L
Power electronics specific weight > 14.1 kW/kg	• WBG high density demonstration: > 14.1 kW/kg
Power electronics cost < $3.3/kW	• Reduced film capacitor requirements: Capacitor specific energy reduced from 9 J/kW to < 5 J/kW • Reduced cooling system requirements and increased MTTF: $Q = P_{out}/P_{loss}$ improved from 10 to over 30

DOE PHEV Charger 2022 targets	Projections for this Project
On-board charger meeting 3.3 kW, 3.5 kg, 0.943 kW/kg	• Integrated 6.6 kW level 2 charger, added mass 1.6 kg, add-on specific weight 4 kW/kg

These goals are achieved through a new *Composite Converter* technology that achieves significant and non-incremental performance gains

Relevance

Specific Project Goals

30 kW drivetrain architecture demonstration

Specification	Target
Average efficiency, US06	97.5%
DC boost ratio	3
Film capacitor specific energy	< 5J/kW
Control bandwidth	2 kHz
Controller overshoot	< 20%
Bus voltage (max)	800 V

WBG high density demonstration

Specification	Target
Bus voltage (max)	800 V
Volumetric power density	≥ 13.4 kW/L
Gravimetric power density	> 14.1 kW/kg
Coolant temperature	105˚C
Peak efficiency	> 97.5%

Above goals have been met.

Specific activities

- Incorporate both Si and WBG power devices and high density packaging. Project results will provide objective data comparing Si and WBG converters optimized to above specifications
- Integrate on-board level 2 charger that reuses powertrain converter modules. The reduced cost and weight enables incorporation of higher-power on-board charging capability.
- Demonstrate reduction in average loss over US06 of factor of 2-4, enabling improved MPGe, reduced temperature rise over standard drive cycles, and increased MTTF
- Demonstrate reduction in film capacitor requirements by factor of at least 2

2016 CY Milestones

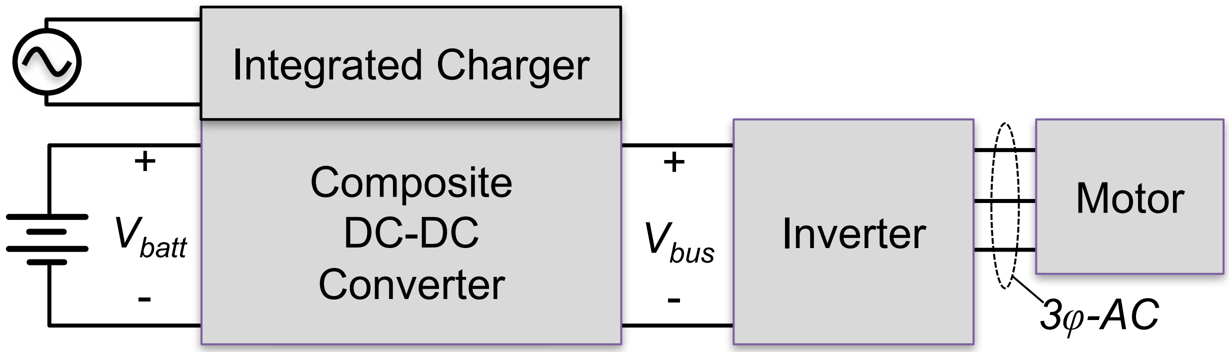
Date	Milestones and Go/No-Go Decisions	Status
March 2016	Milestone: Design of new SiC dc-dc and inverter modules complete	Complete
June 2016	Milestone: DC-DC/Inverter powertrain construction complete	Complete
October 2016	Milestone: Demonstrate DC-DC/inverter system with US06 drive cycle	Complete
December 2016	Final Milestone: Modular powertrain system demonstration: achieve PE system efficiency ≥ 97.5% at V_{batt} = 250 V, machine line-line peak voltage of 650 V, at 50% of rated power.	Complete

Overall project: experimental demonstrations of

- Si-MOSFET composite boost dc-dc converter, 20 kHz
- Si-MOSFET integrated level 2 charger
- SiC-MOSFET inverter
- SiC-MOSFET composite boost dc-dc converter, 240 kHz
- SiC-MOSFET integrated level 2 charger

30 kW nominal, 250 V battery, 650 V dc bus

Approach / Strategy

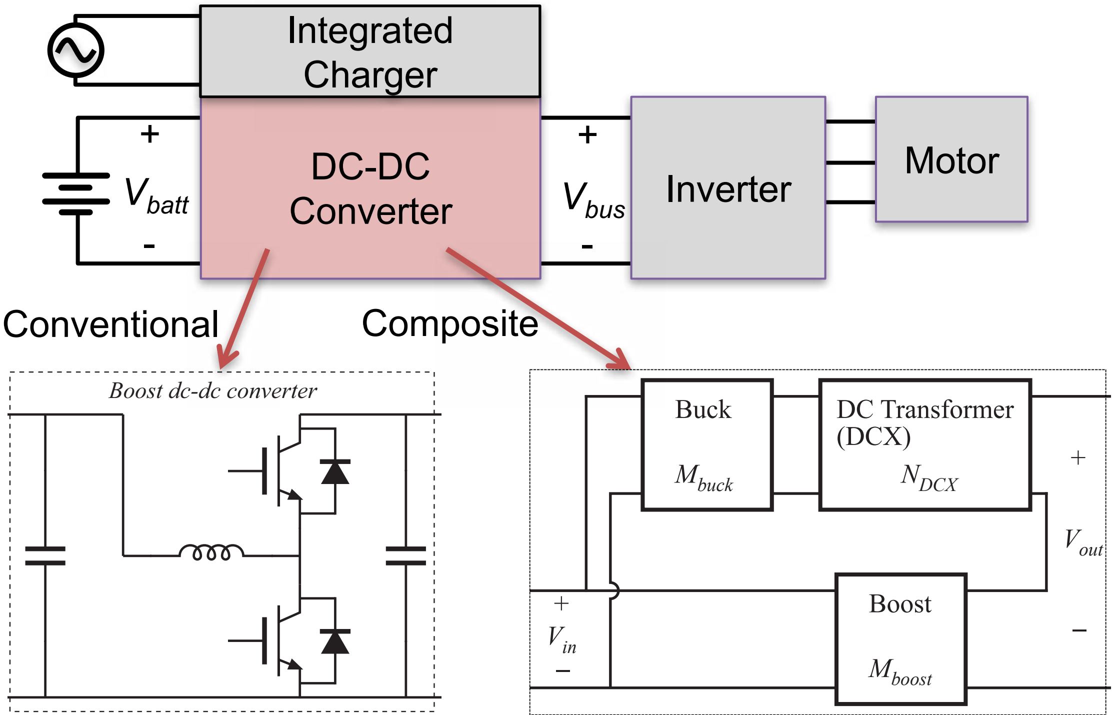


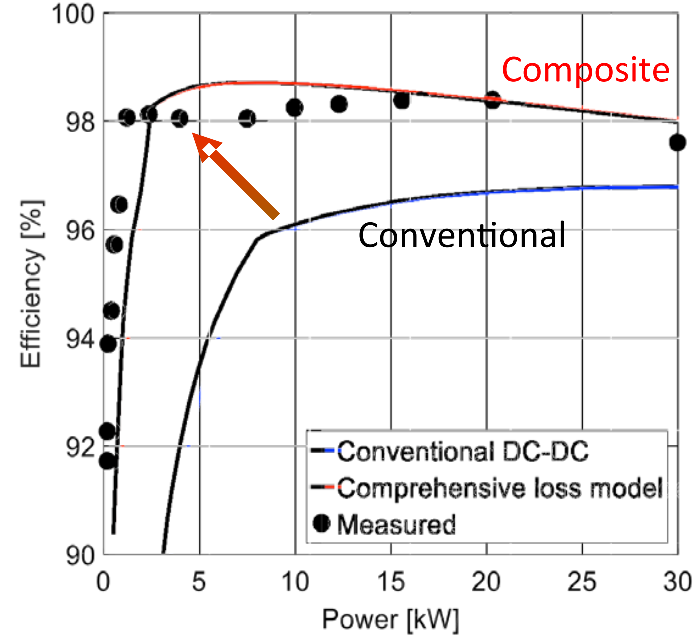
Demonstrate new composite converter topology that leads to fundamental performance improvements including average efficiency, film capacitor size, and on-board charger size.

Technology	Switching frequency	CAFE average efficiency	Relative Film Capacitor V_{rated} I_{rms}
Conventional boost, Si IGBT	10 kHz	93.4%	1.0
Conventional boost, SiC MOSFET	240 kHz	95.7%	1.0
New composite, Si MOSFET	20/33 kHz	96.8%	0.3
New composite, SiC MOSFET	240 kHz	97.4%	0.3

Composite converter technology improves average efficiency and film capacitor size.
Increase of switching frequency improves magnetics size.

Approach / Strategy





Efficiency improvement in proposed composite architecture vs. conventional boost: V_{batt} = 250 V, V_{bus} = 650 V

Conventional boost: multiple Si IGBT die are connected in parallel in multichip power semiconductor module

- 10 kHz switching frequency
- Poor partial power efficiency
- High rms current in DC bus capacitors
- Efficiency of boost converter dominates system efficiency

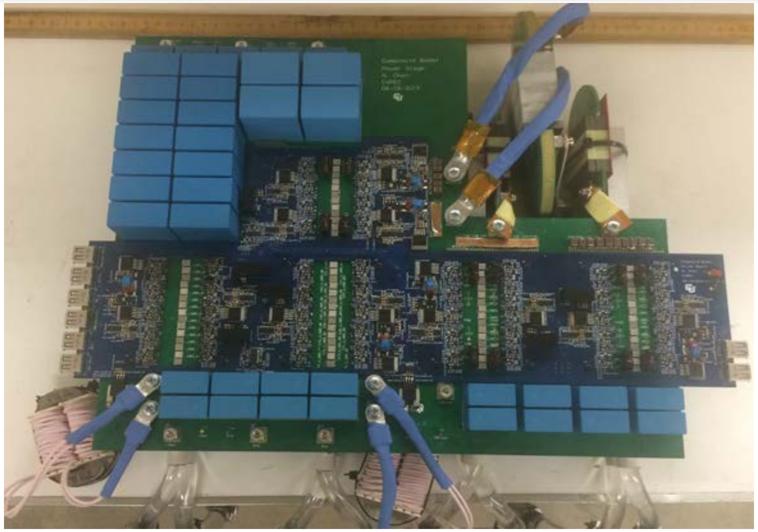
Proposed composite boost converter architecture

Partial-power dc-dc converter modules

- Semiconductor area is same as in conventional boost
- Improved efficiency by reduction of switching loss and magnetics ac loss, through use of passthrough modes and reduced module voltages
- Substantially reduced RMS capacitor currents
- Substantially reduced operating temperatures and failure rates

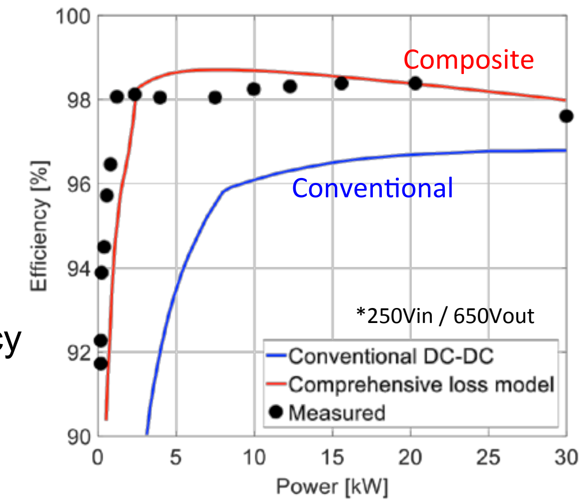
Fundamental improvements in performance arising from new superior converter architecture

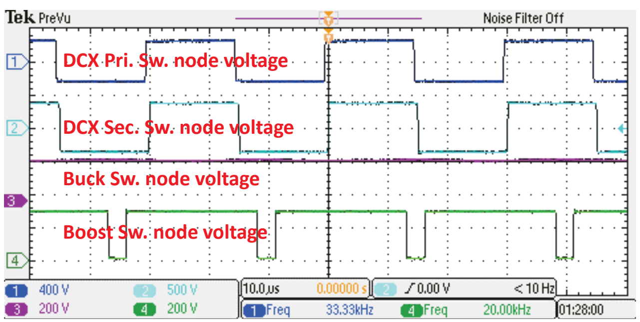
Si MOSFET Composite Boost Converter



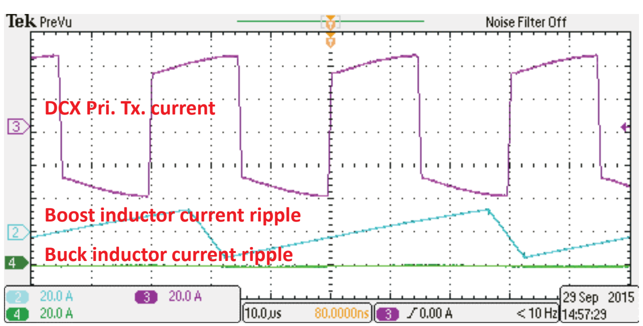
Assembled 30 kW laboratory prototype

Measured efficiency



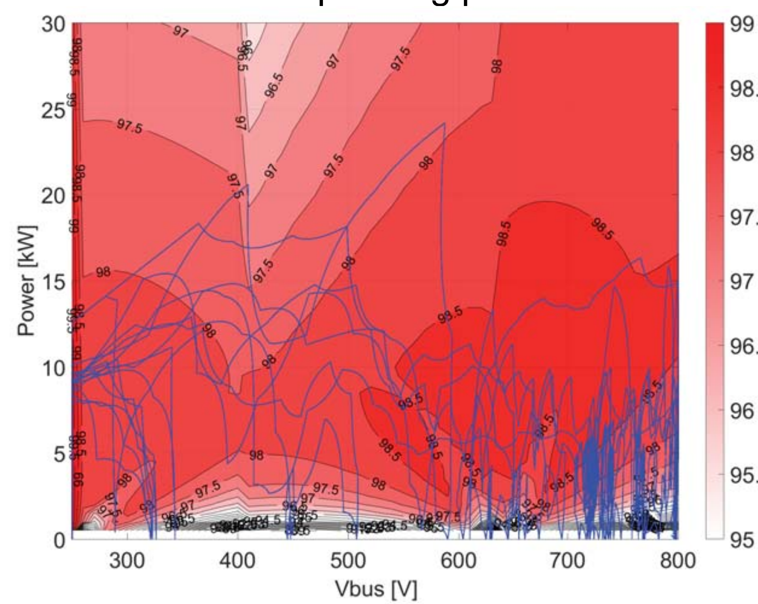


Operating waveforms at 250V:650V, 50% power



DCX f_s = 33 kHz
Buck, boost f_s = 20 kHz

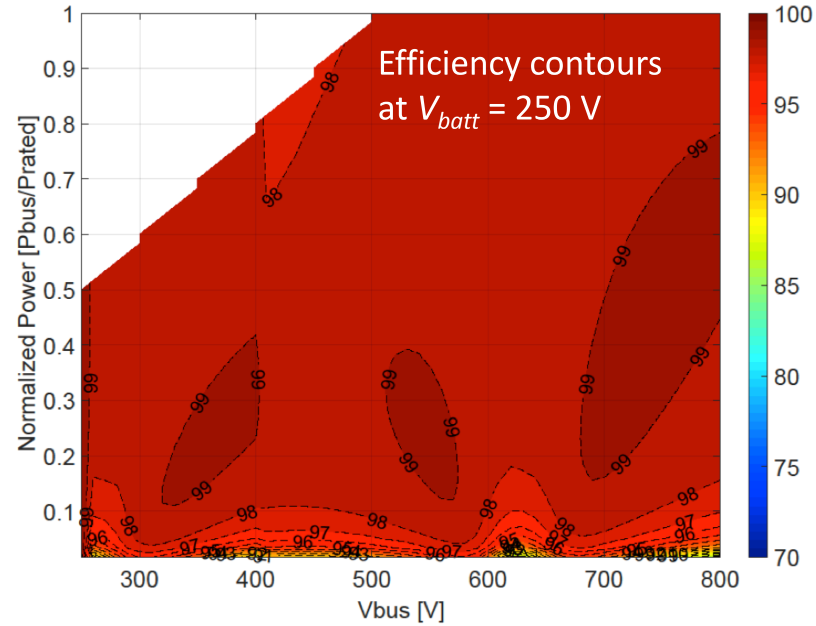
Complete efficiency contours, with superimposed US06 operating points

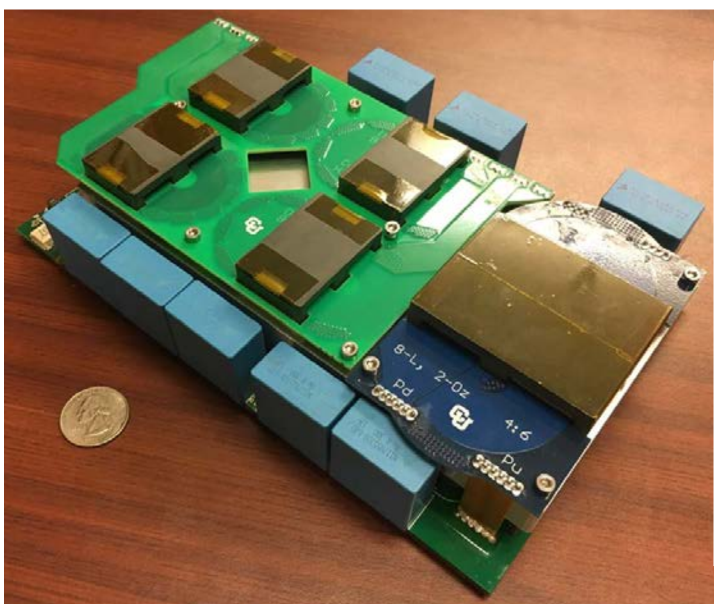


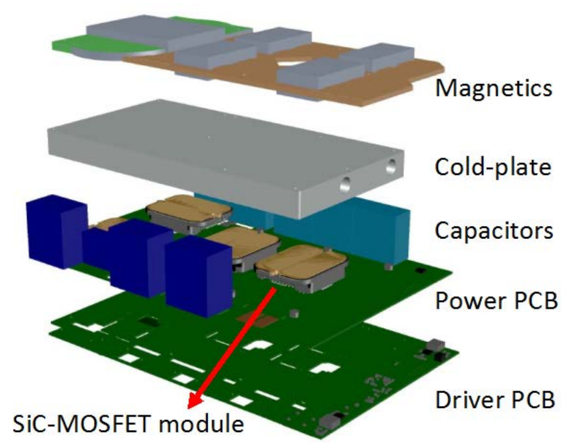
Technical Accomplishments

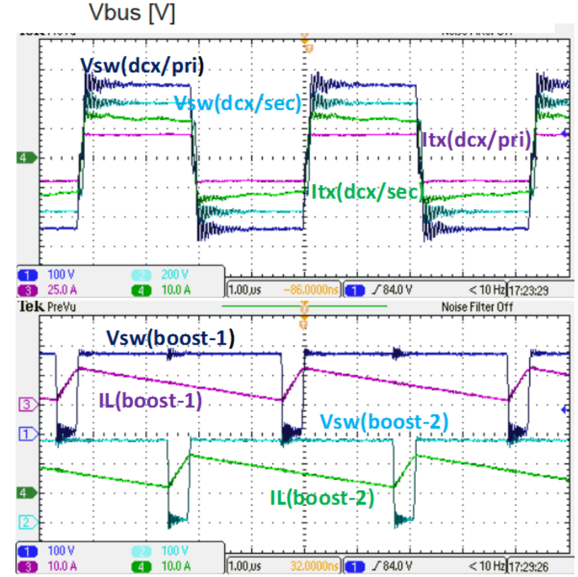
High Density SiC Prototype Composite Boost Converter

- Power density of 23 kW/L, 20 kW/kg in boost dc-dc system including magnetics
- Rated power 27 kW continuous, 39 kW peak using 900 V 10 mΩ SiC MOSFETs
- Switching frequency 240 kHz
- Input battery voltage 200-300 V, output dc bus voltage 200-800 V
- Ferrite planar magnetics
- Film capacitor specific energy: 0.19 J/kW, significantly better than < 5J/kW goal





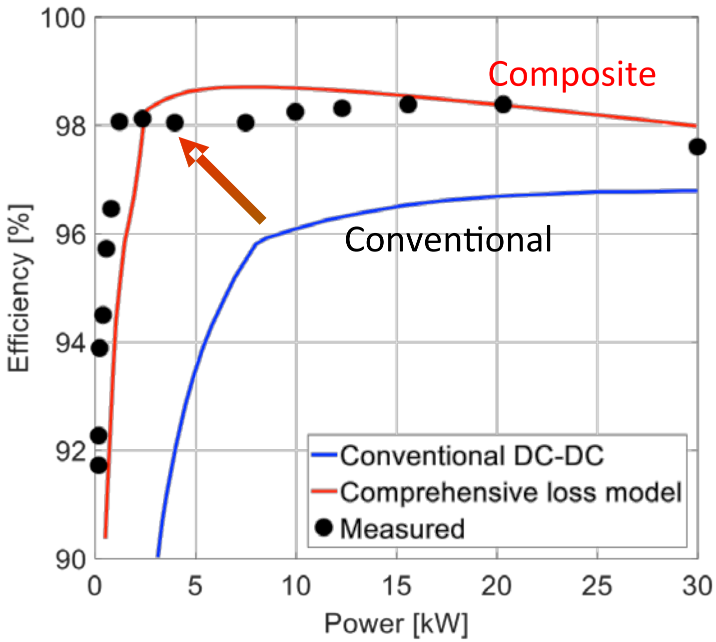




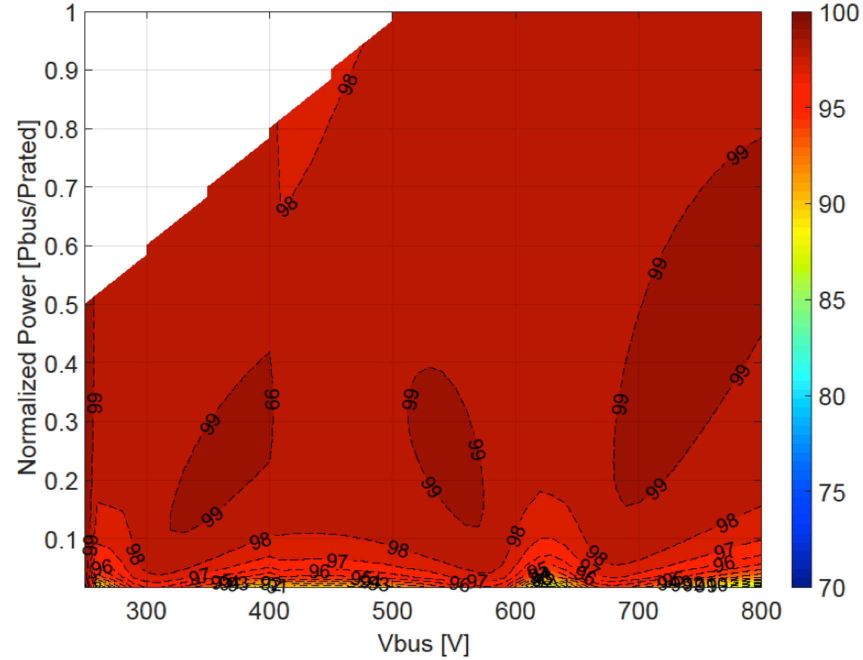
Waveforms at 250:650V, 40% power

Composite Boost Converter Efficiency

Efficiency curve of 30 kW Si composite boost converter at V_{batt} = 250 V, V_{bus} = 650 V



Efficiency contours of 27 kW SiC composite boost converter, at V_{batt} = 250 V



Converter	Si-IGBT Conv. Boost[1]	Si-MOSFET Composite boost	SiC-MOSFET Conv. boost	SiC-MOSFET Composite boost
Switching frequency	10 kHz	20/33 kHz	240 kHz	240 kHz
CAFE efficiency	94.7 %	98.1 %	96.1 %	97.8 %
CAFE $Q = P_{out}/P_{loss}$	17.9	51.6	24.6	44.9
Magnetic volume [mL]	343	372	136	82

An Estimate of the Effect of Drive Cycle Loss on MTTF

MTTF calculations based on failure rates of power transistors, gate drivers, and film capacitors

- Published failure rates of IXYS automotive-qualified gate drivers: scale approximately with rated current
- Si IGBT, Si MOSFET, and SiC MOSFET failure rates: based on available manufacturer data and accepted calculation practices
- Operating temperatures based on weighted drive cycle loss (55% UDDS, 45% HWFET)
- Same thermal resistance model assumed in all cases

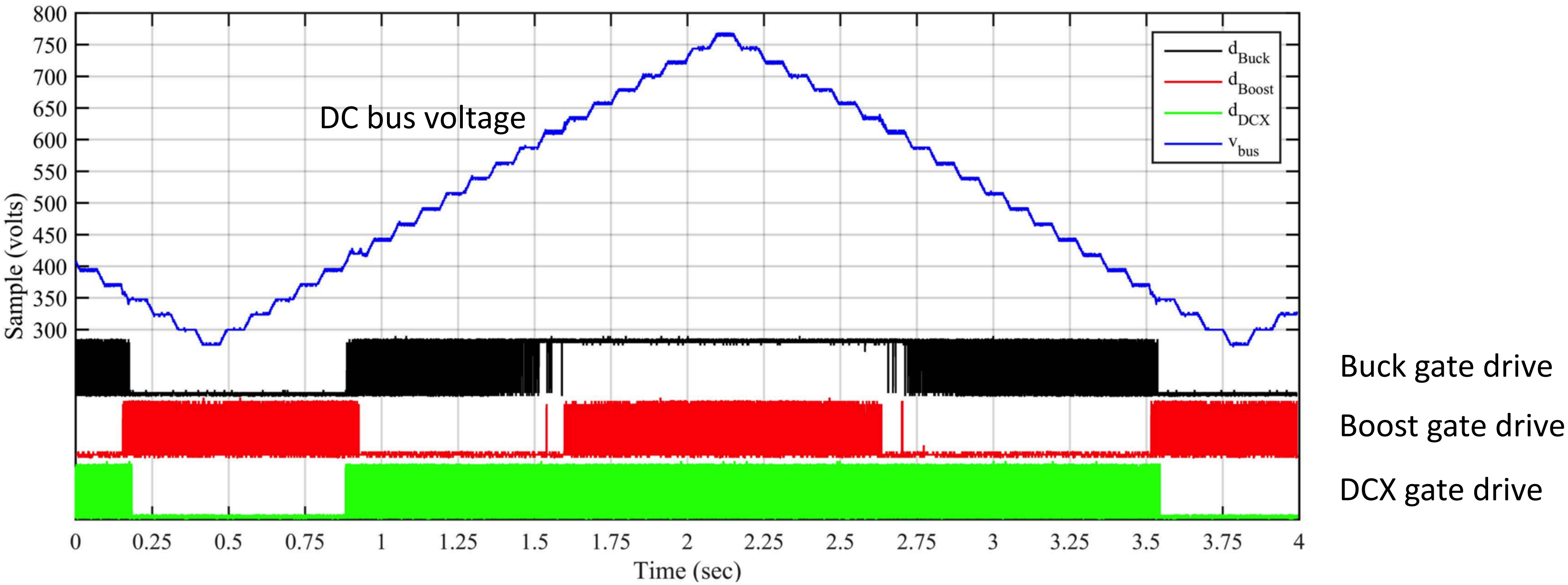
	Si IGBT, conventional	SiC MOSFET, conventional	Si MOSFET, composite	SiC MOSFET, composite
Weighted efficiency	94.7%	96.0%	98.1%	98.2%
Weighted $Q = P_{out}/P_{loss}$	17.9	24.6	51.6	60
Average temp	104 C	88 C	75 C	74 C
MTTF	**122 khrs**	**553 khrs**	**355 khrs**	**1208 khrs**

The above calculations illustrate only the effect of drive cycle efficiency on lifetime of semiconductors, gate drivers, and film capacitors for a given set of system assumptions. These numbers also account for differences in required number of gate drivers and film capacitors.

Control of Composite DC-DC Converter

A system controller has been implemented and experimentally demonstrated:

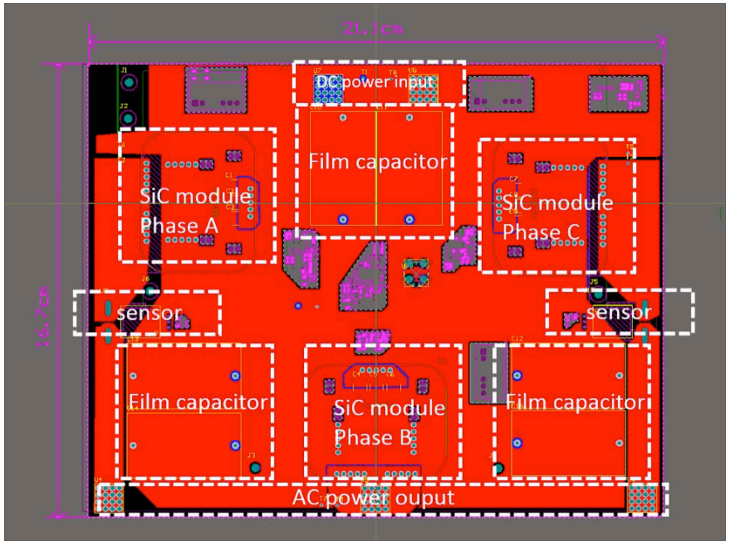
- Automatic mode switching of partial-power converter modules
- Damping of module resonances, even when modules operate in passthrough mode
- Avoidance of discontinuities and controller dead zone problems at mode boundaries via DZAM control



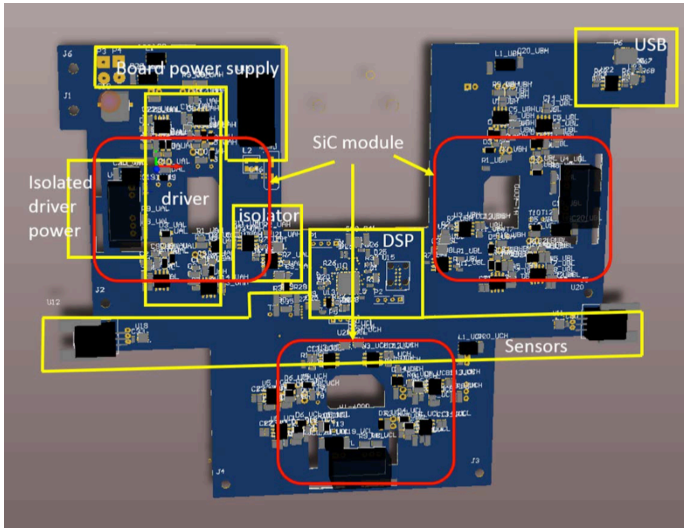
Experimental voltage and gate driver waveforms of closed-loop Si composite boost converter, with 294 V battery input and staircase voltage reference. The DC bus voltage is controlled between approximately 294 V and 750 V in this test. Reliable operation with minimal overshoot is attained.

SiC Inverter Prototype

- Same inverter used with Si and SiC composite boost experiments
- Each phase employs 2x Cree 1200 V 25 mΩ MOSFETs in half bridge configuration
- Rated power: 30 kW. Estimated power density: 16 kW/L
- Measured efficiencies at final milestone point (250V:650V, 50% power):
  - Composite boost 98.26%
  - Inverter 99.43%
  - Total system: 97.7%
- Field-oriented control, 2 kHz bandwidth goal met



Power PCB, 13 oz cu



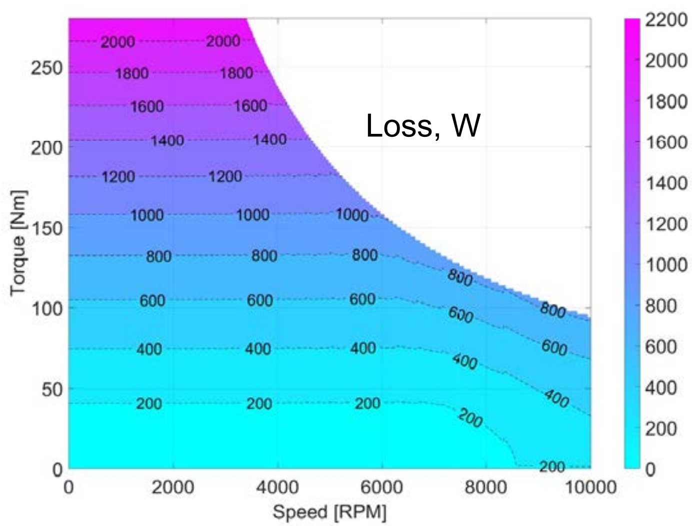
Driver and controller PCB, 4 oz cu

Inverter Loss Models

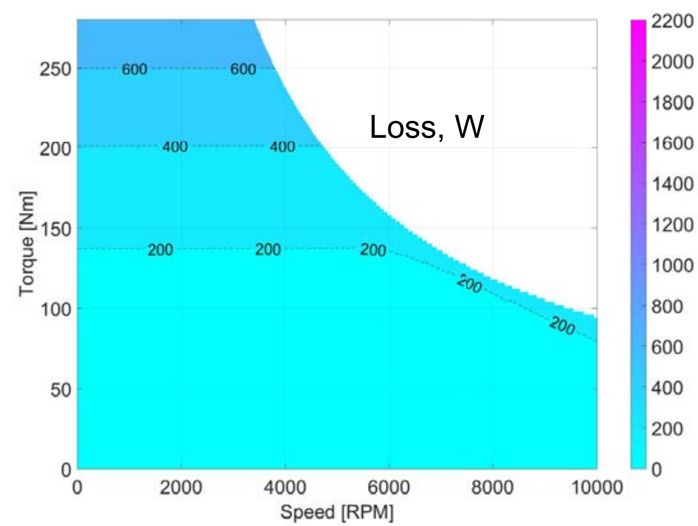
- Detailed models of conduction and switching losses were developed and experimentally calibrated, see references for details
- Inverter losses modeled for 600V and 1200 V Si IGBT and for 1200 V SiC MOSFET inverters
- Comparison of approaches at 80 kW, 5 kHz

Device	600V Si-IGBT Infineon IKW75N60T	1200V Si-IGBT Infineon IKW40T120	1200V SiC-MOSFET Cree C2M0025120B and Cree CPW5-1200-Z050B
V_{dc}	350 V	800 V	800 V
Semiconductor die area [mm^2]	3900	3464	1801
Current rating per switch	825 A	360 A	360 A
Current power density [A/mm^2]	1.27	0.62	1.20

600 V Si IGBT
Inverter loss contours at V_{bus} = 350 V, switching frequency = 5 kHz



1200 V SiC MOSFET
Inverter loss contours at V_{bus} = 800 V, switching frequency = 5 kHz

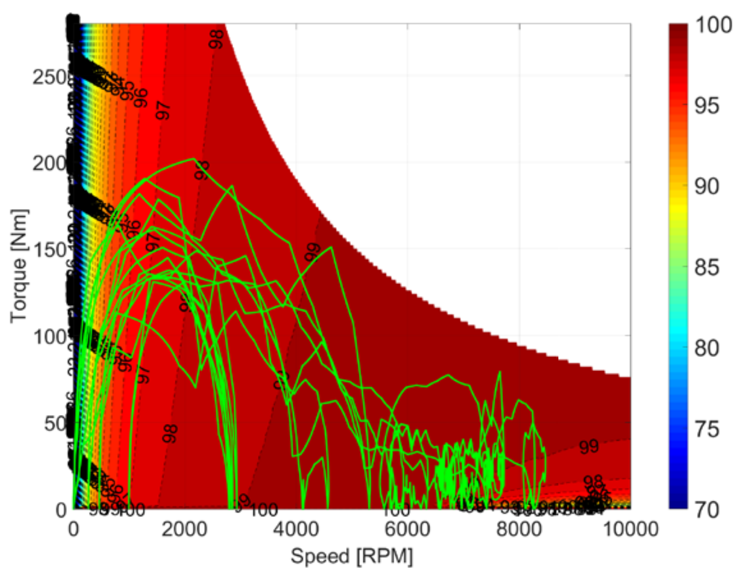


SiC Inverter Performance

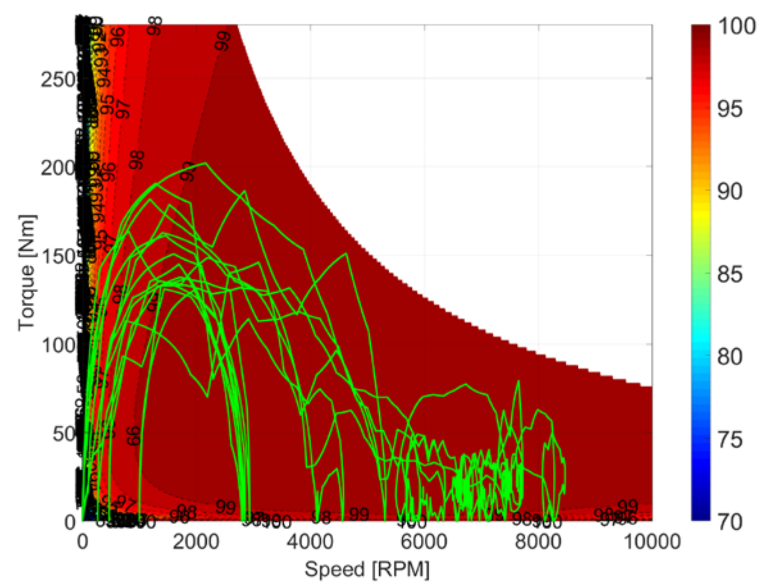
Comparison of predicted drive cycle inverter efficiency, based on calibrated loss models

	600V Si-IGBT	1200V Si-IGBT	1200V SiC-MOSFET
Rated power	80 kW	80kW	80kW
Switching frequency	5kHz	5kHz	5kHz
UDDS avg. e ciency	97.51%	98.14%	99.39%
HWFET avg. e ciency	99.06%	99.30%	99.72%
US06 avg. e ciency	98.60%	98.86%	99.65%
CAFE avg. e ciency	98.21%	98.66%	99.54%
CAFE Q factor	54.79	73.74	215.69
Peak loss	2.2 kW	1.5 kW	0.8 kW

- Based on converter loss models calibrated in our laboratory, and on mechanical parameters of Nissan Leaf
- Comparison of total loss over drive cycles
- SiC inverter loss is 25% of 600V Si IGBT loss at 5 kHz

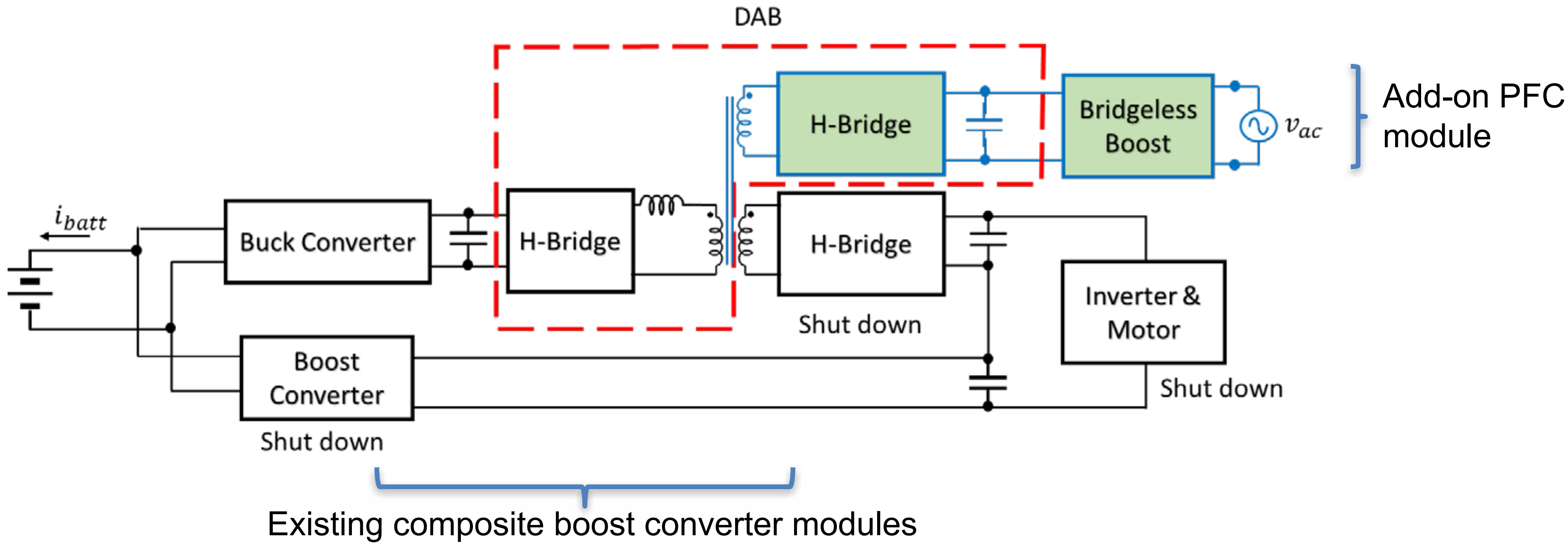


1200 V Si-IGBT inverter efficiency characteristics with superimposed US06 trajectory



1200 V SiC-MOSFET inverter efficiency characteristics with superimposed US06 trajectory

Integrated Level 2 Charging

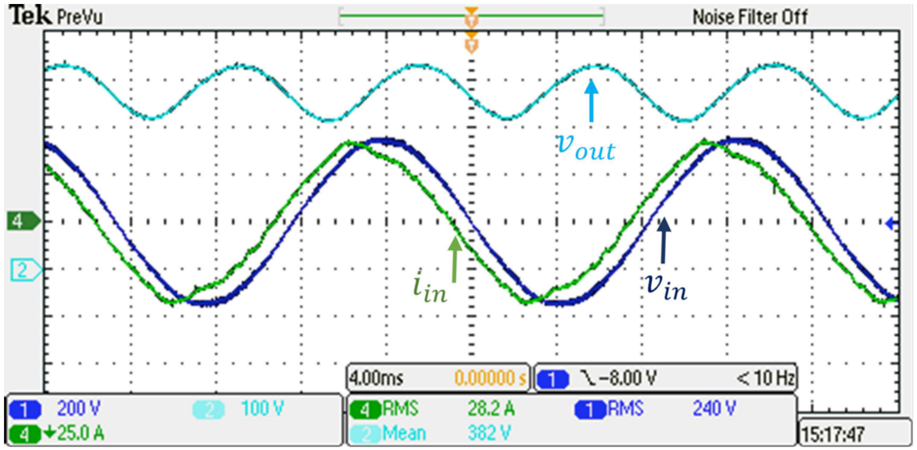


Integration of charging function:

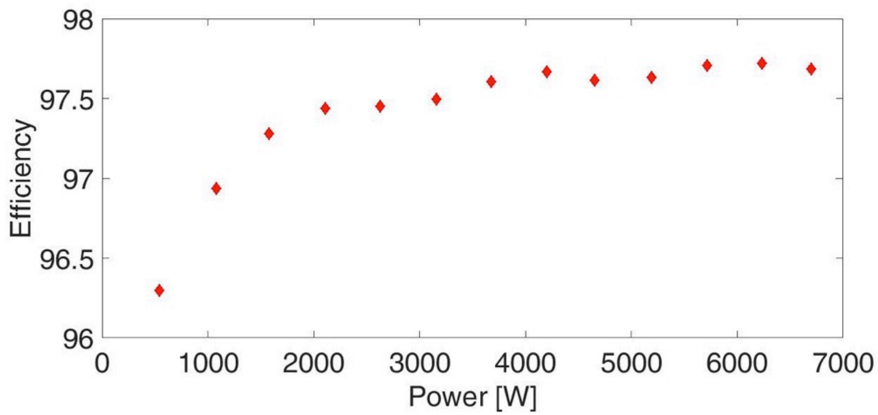
- Composite boost modules are re-purposed for charging, to provide the functions of galvanic isolation and regulation of battery current
- Add only a PFC waveshaping stage and bulk energy storage capacitor (shown in green)
- Could achieve on-board charging at powers up to the ratings of the composite converter modules, with relatively low added size and weight

Summary of Experimental Results

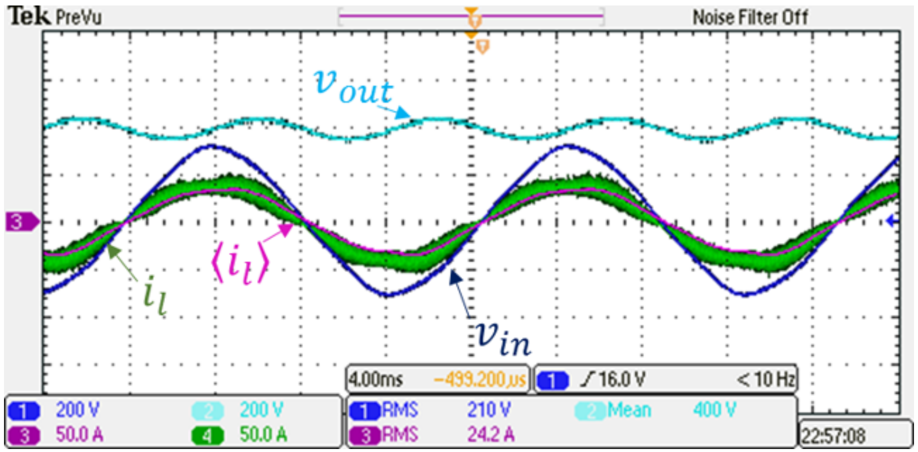
Si PFC waveforms at 6.6 kW, 240 Vac
f_s = 20 kHz, DCM



Measured charger efficiency data



SiC PFC waveforms at 5 kW, 240 Vac
f_s = 120 kHz, CCM



Demonstrated in this 30 kW system:

- Level 2: 6.6 kW charger demonstrated experimentally, with both Si and SiC versions
- Added power density 5.9 kW/kg, substantially exceeds 0.94 kW/kg target (3.3 kW / 3.5 kg)
- In a scaled 100 kW system, charging from a 240 V 100 A circuit would be possible

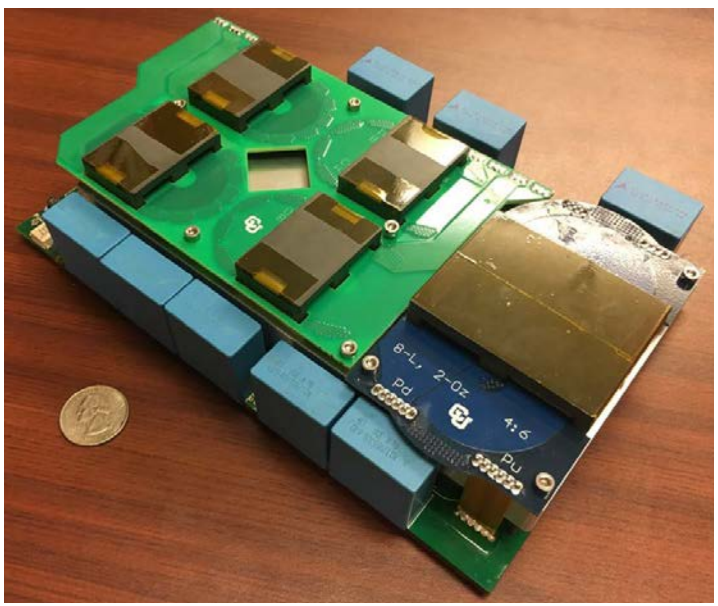
Responses to Previous Year's Reviewer Comments

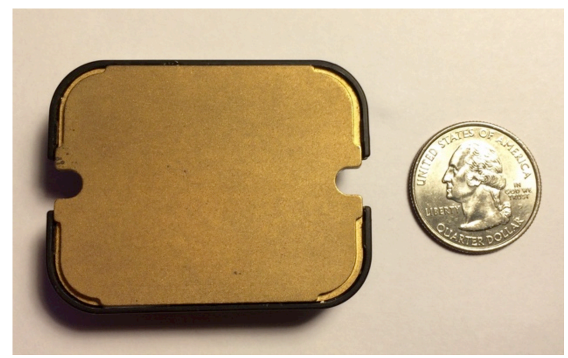
This project was not reviewed last year.

Partners and Collaborators

Subcontractor: Wolfspeed/Cree

- Supplier of 900 V and 1200 V SiC-MOSFET devices
- Packaging of SiC H-bridge modules
- High density system assembly and thermal design of SiC composite boost prototype





Proposed Future Work

This project has been completed and all milestones have been demonstrated.

Follow-up directions:

- Scale to higher powers and voltages as appropriate, with composite architecture tailored to application requirements and to available WBG devices
- Integration of dc-dc, inverter, and charger functionality into a single high-density package to demonstrate complete system functionality
- Development of hierarchical modular control to simplify scaling to higher power and larger module number
- Addition of new functionality to the modular composite converter approach
    - Additional charging functionality
    - Boost function integrated into battery pack, with higher voltage dc interconnection to inverter
- Refine characterization of MTTF of competitive approaches

Collaboration with

- One or more OEMs to provide application directions
- National labs to provide CHIL testing and higher-power test facilities

Any proposed future work is subject to change based on funding levels

Summary

- Near-constant 98% efficiency demonstrated in 20/33 kHz Si composite boost converter at 250:650 V over wide power range: 3% to 100% of rated power
- High-density 240 kHz SiC composite boost converter demonstrated, with 23 kW/L and 20 kW/kg power densities including magnetics, and similar efficiency
- SiC inverter module has been demonstrated and characterized. Field-oriented control algorithms have been demonstrated with PM machine under US06.
- System control algorithms have been developed leading to stable and reliable operation with mode switching, current limiting, reversal of power flow, and damping of module resonances. New DZAM algorithm has been demonstrated experimentally.
- Final milestone completed—measured efficiencies at 250V:650V, 50% of rated power:
  - Si composite boost 98.26%
  - SiC inverter 99.43%
  - Total system efficiency 97.70%
- 6.6 kW SiC add-on charger module has been demonstrated. On-board level 2 charging can be achieved with > 5 kW/kg power density, by taking advantage of the modular nature of the composite converter approach.